A Comprehensive Modeling Approach Towards Understanding and Prediction of the Alaskan Coastal System Response to Changes in an Ice-diminished Arctic

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LONG-TERM GOALS

Our research combines state-of-the-art regional modeling of sea ice, ocean, atmosphere and ecosystem to provide a system approach to advance the knowledge and predictive capability of the diverse impacts of changing sea ice cover on the bio-physical marine environment of coastal Alaska and over the larger region of the western Arctic Ocean. The focus of this project on seasonally ice-free Alaskan coasts and shelves is in direct support of the ‘Coastal Effects of a Diminished-ice Arctic Ocean’ and littoral studies of interest to the U.S. Navy.

Given the continued warming and summer sea ice cover decrease in the Arctic during the past decades, this research will have broader and long-term impacts by facilitating studies of the potential increased exploration of natural resources along the seasonally ice-free northern Alaskan coasts and shelves and of the use of northern sea routes from the Pacific Ocean to Europe. Such activities will change the strategic importance of the entire pan-Arctic region. The research will allow a better understanding and planning of current and future operational needs in support of the continued US commercial and tactical interests in the region.

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OBJECTIVES

The main science hypothesis to be addressed in this project can be formulated as follows. The recently observed dramatic decrease of summer sea ice cover in the western Arctic Ocean is driven by two main, primarily local factors: (i) the oceanic heat advection of summer Pacific Water via the Alaska Coastal Current and (ii) the positive ice-albedo feedback. To understand physical processes and air-sea-ice interactions involved in these two driving factors, detailed studies, including historical and new observations and very high-resolution modeling, of the Alaska coastal environment are required. The following five specific science goals are proposed to address those requirements in support of the main hypothesis of this project:

1. Explore feedback processes among sea ice, ocean and atmosphere leading to recent and possible future summer decreases of sea ice cover in the Western Arctic Ocean;

2. Quantify impacts of oceanic and atmospheric forcing on regional sea ice cover and its variability;

3. Determine effects of changing sea ice, ocean dynamics and atmospheric circulation on the Alaskan coastal ecosystem (due to temporal and spatial variability);

4. Establish numerical requirements for an optimal hindcast and prediction of environmental conditions in the Alaskan coastal system;

5. Provide guidance for optimal design of an integrated observing system of the Alaskan coastal environment.

APPROACH AND WORK PLAN

This work builds on a wealth of Arctic modeling expertise and progress at the Naval Postgraduate School, University of Colorado, and University of South Florida to develop state-of-the-art, regional ocean, sea ice, atmosphere and ecosystem models satisfying requirements for studying this coastal system (Maslowski et al., 2007a, 2007b; Maslowski et al., 2004; Maslowski and Lipscomb 2003; Maslowski and Walczowski, 2002; Maslowski et al., 2001; Maslowski et al., 2000; Clement et al., 2005; Clement et al., 2007; Cassano et al., 2001; Cassano et al., 2006a, 2006b, Cassano et al., 2007; Walsh et al., 2004; Walsh et al., 2005). This effort will use available historical and new data for validation or initialization.

Atmospheric Modeling: The group at CU plans to complete a suite of varied horizontal resolution atmospheric model simulations over a model domain centered on the Alaskan north slope using ERA40 and/or ERA Interim initial and lateral boundary conditions and sea ice extent from satellite observations. All simulations are to be nested within coarser resolution regional atmospheric model domains that cover a larger portion of the Arctic, such that the change in resolution between any domain forcing data (either from global reanalyses or coarser resolution atmospheric model domains) and that domain's horizontal resolution is no greater than a factor of 5.

Ice-Ocean Modeling: The NPS personnel led by Dr. W. Maslowski have developed an eddy resolving configuration of the coupled ice-ocean model for the pan-Arctic region. The model at $1/48^{o}$ and with 48 vertical layers has run the spinup integration, which will continue beyond 2009, subject to the availability of large amount of computer resources and job competition at each computer center.

Ecosystem Modeling: research is led by Dr. John J. Walsh at the University of South Florida. The milestones of this project involve completion of the following four tasks:

1. Modify the existing 9-km bio-model of Walsh et al. (2004, 2005) to allow decadal integrations

2. Develop a biological (N-P-Z) model at eddy-resolving resolution and over the same domain as the ocean-ice model

3. Complete two decadal simulations (configured at increasing spatial resolution) of the biological model forced with high-resolution ice-ocean and atmospheric model output

4. Analyses (inter-comparison & validation with data) of results to address the main science goals

WORK COMPLETED / RESULTS

University of Colorado

During the past year we have worked towards the development of a polar optimized version of WRF, which will be suitable for the atmospheric modeling portion of this project. This work included 220 months of simulations on small regional domains (with horizontal resolution of 10 and 50 km) to evaluate a range of model physics parameterizations for shortwave and longwave radiation, cloud microphysics, and boundary layer processes. Based on results from these small domain simulations we ran a limited set of pan-Arctic domain simulations (50 km horizontal grid spacing) to evaluate model physical parameterizations (shortwave and longwave radiation and boundary layer processes), treatment of the model lower boundary condition (fractional versus non-fractional grid point sea ice), and data assimilation (gridded four-dimensional data assimilation and spectral nudging). These simulations were conducted for 4 months (January, April, July, and October 2007) and were run as sets of 3 member ensembles (with 1, 14, and 28 day spin-up times used to generate the 3 member ensembles). In total we've run 120 months of simulations as part of the pan-Arctic WRF evaluation.

Results from the small domain and pan-Arctic domain simulations are currently in preparation for publication in peer reviewed journals, and we expect to submit 3 articles based on the findings from these simulations in the next year. One paper will focus on the results of the radiation and microphysics evaluation simulations for a North Slope of Alaska model domain. The second paper will focus on the results of the microphysics and boundary layer simulations over Canadian archipelago and Greenland domains. The final paper will focus on the results of the pan-Arctic domain simulations.

Based on the extensive suite of small domain and pan-Arctic domain simulations that have been completed we have identified a preferred configuration of WRF that will be used for all subsequent Polar WRF simulations for this project. Using this model configuration we will run the following simulations:

- 50 km horizontal grid spacing, 40 vertical levels, 1979 to 2009 forced with ERA-Interim
- 25 km horizontal grid spacing, 40 vertical levels, 1979 to 2009 forced with ERA-Interim
- 9 km horizontal grid spacing, 40 vertical levels for shorter periods of time, forced with ERA-Interim

We have recently gained access to the ERA-Interim data and are in the process of implementing this data as forcing data for our WRF simulations.

A secondary area of research has focused on global climate model simulations of reduced sea ice conditions in the Arctic using CAM3. Results from these simulations will complement our analysis of the impact of model resolution on Arctic simulations. One paper, based on this research, has been published (Higgins and Cassano, 2009) and was highlighted as an article of note in the *Journal of Geophysical Research* and a second paper is currently in preparation.

Funding from this project has provided partial salary support for the University of Colorado co-PI (1 summer month), an associate scientist, and a graduate student at the University of Colorado.

Naval Postgraduate School
A major progress with eddy-resolving ice-ocean model configuration and simulation has been made at NPS during 2009. High-resolution runs configured at 1/48^o or ~2.4 km grid have been designed to further understand the role of oceanic circulation, advection of warm water from the Chukchi shelf into the basin and significance of mesoscale eddies (Maslowski et al., 2008) in the recent warming and sea ice melt in the western Arctic Ocean (Maslowski and Clement Kinney, 2009).

Earlier analyses of results from the 1/12^o or ~9.2 km model have demonstrated a relative importance of the internal oceanic forcing of sea ice melt. In particular, the thermodynamic interactions at the ice-ocean interface in the western Arctic Ocean have been focused on. Under-ice ablation by anomalously warm water advected from the Chukchi shelves and distributed at the subsurface layer in the western Arctic Ocean by mesoscale eddies has been found to explain a significant fraction of the total variance of sea ice thickness. We have found that the excess oceanic heat that in recent years has been accumulating below the surface during summer and it might be a critical initial factor in reducing ice concentration and thickness in the western Arctic Ocean at the early melting season and onwards the following year.

The eddy-resolving model simulates mesoscale eddies with radius as small as 15 km, which are common along the northern Alaskan shelf and slope in the Chukchi and Beaufort seas. The frequency of their occurrence and magnitude of rotational speed are much higher compared to the 9-km model. In addition, the modeled export of summer Pacific Water from the Chukchi shelf (Figure 1a) compares well with an image of sea surface temperature from the Moderate Resolution Imaging Spectrometer (MODIS) (Figure 1b). Both the intensification of warm water outflow between Pt. Barrow and the eastern flank of Barrow Canyon and the instability of this flow downstream with a double-eddy feature in the basin are quite realistically represented. According to our model results and observations (Okkenen et al., 2009) majority of oceanic heat from the Chukchi shelf is delivered along this pathway via the Alaska Coastal Current. The width of the coastal current as well as its buoyancy and strength of the flow dramatically improve in the eddy-resolving model simulation. In addition to gains due to the spatial resolution the complex bathymetry of this region is more realistic in the high resolution configuration which contributes to the overall improvement of oceanic circulation and shelf basin exchanges. Continued simulation with realistic interannual atmospheric forcing through the 2000s is expected to provide significant insights into the ocean dynamics and its quantitative contribution to sea ice melt in the western Arctic.

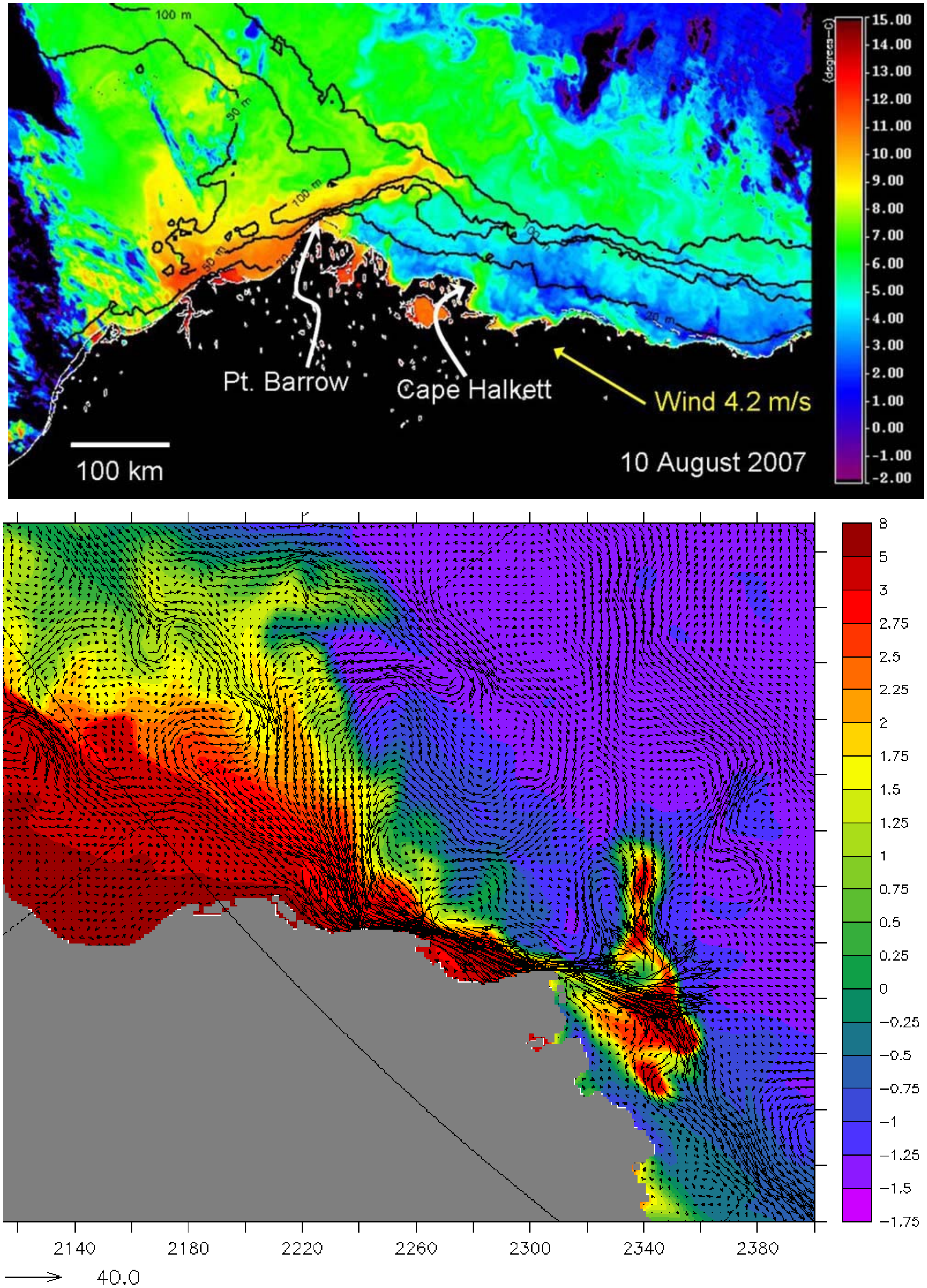

Figure 1. Moderate Resolution Imaging Spectroradiometer (MODIS) sea surface temperatures for 10 August, 2007 (Okkonen et al., JGR 2009) (top). Upper ocean temperature (color shading; ^{o}C) and velocity (cm/s) along the Arctic Alaskan coast on August 31, 1983 from an eddy-resolving (1/48^{o}) coupled ice-ocean model of the pan-Arctic region (bottom).

Another area of major progress is with sea ice simulation using the eddy-resolving model. Figure 2 shows snapshots of winter sea ice divergence and shear 30 days apart, for December 30 and January 30. The positive divergence (red) is first (12/30) seen in the Bering Strait region and in the basin with the convergence further south, especially along the Alaskan Chukchi coast as well as along the Siberian coast and far east in the Canadian Archipelago. A month later, the Alaskan coast and the Chukchi shelf are dominated by divergence with some intermittent convergence zone in the vicinity of the Barrow Canyon and along the Chukchi continental slope. The respective figures with shear show much more complex structure yet their end effect might be similar to the divergence field. Such deformations as openings and fractures in the ice cover in winter remove heat from the ocean underneath and produce ice (Kwok et al., 2007). Given the fact that ice thickness re-distribution and oceanic heat release in winter might be important processes affecting the sea ice cover the following melt season their realistic representation is critical. Once the interannual integration of the eddy-resolving model is completed through the 2000s we plan detailed analyses and comparison of RGPS data regarding deformation related ice production, regional ice drift and export and small scale kinematics following Kwok et al. (2007).

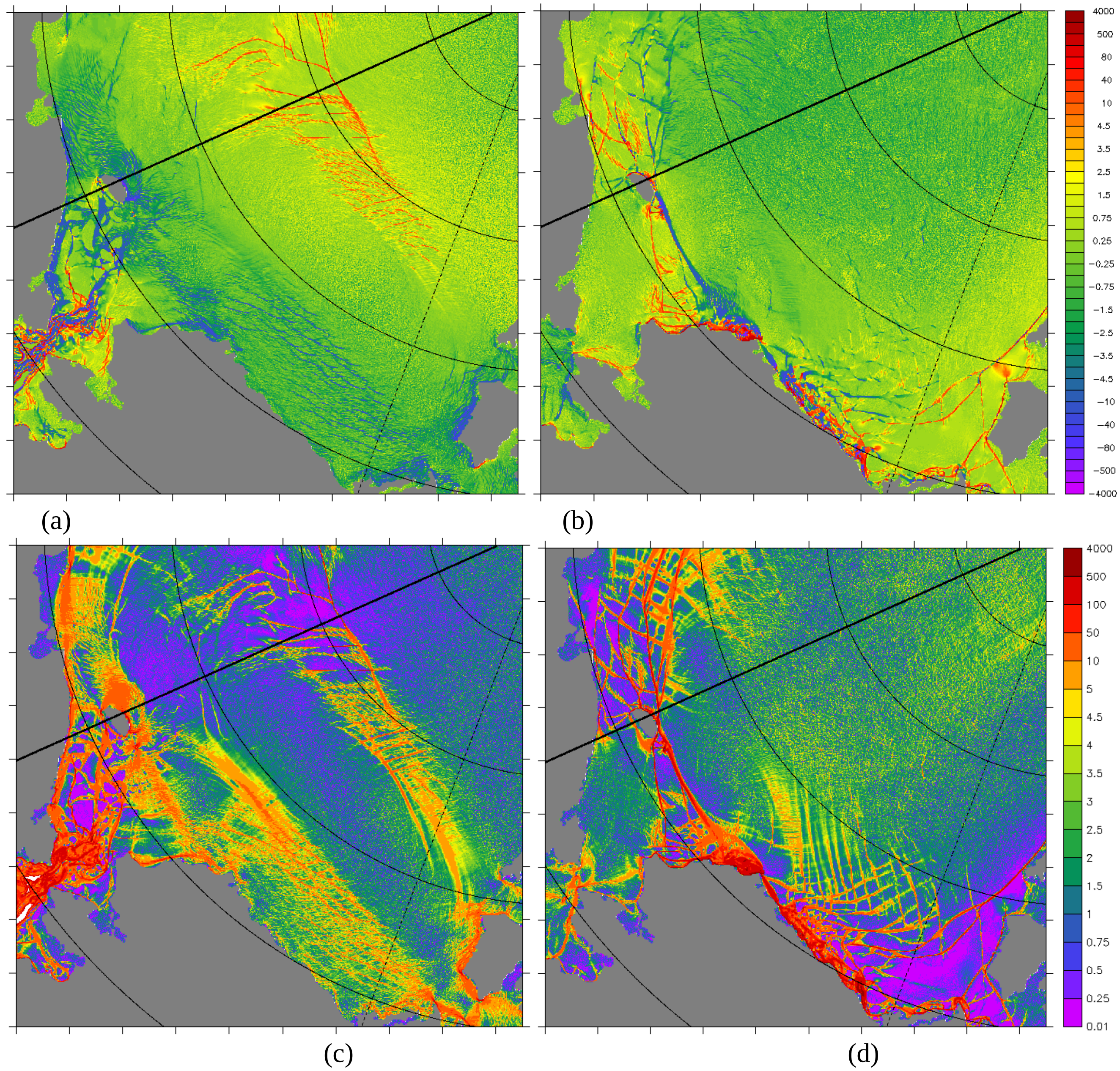

Figure 2. Snapshots of modeled sea ice deformations: divergence (top) and shear (bottom) on December 30, 1983 (left) and January 30, 1984 (right) from an eddy-resolving (1/48^{o}) coupled ice-ocean model of the pan-Arctic region.

The eddy-resolving model is computationally a very large problem requiring substantial computer resources. These two factors determine the actual rate of model integration, which is further slowed down by the actual turn out time (in contrast to run-time) of each model run. All the above translate into a delay of the planned completion of model multi-decadal simulations.

University of South Florida

As part of the USF contribution to the joint NOPP project on "A comprehensive modeling approach

towards understanding and prediction of the Alaskan coastal system response to changes in an ice-diminished Arctic", a nitrogen isotope budget for contiguous Arctic marine ecosystems of the Gulf of Alaska, the northwestern Bering Sea, the Chukchi Sea, and East Siberian Sea, as well as the western (Mackenzie River plume) and eastern (Lancaster Sound) sectors of the Beaufort Sea was recently completed. A manuscript for submission to Deep-Sea Research is now being prepared (Walsh et al., 2009).

Based on the results of the isotope budget, we have selected the following 28 explicit state variables for the coupled biophysical model: wind; temperature; salinity; ice cover; spectral light; u, v, w vectors of flow; vertical mixing coefficient, Kz ; UV-sensitive colored dissolved organic matter (CDOM); equivalent labile DOC, DON, and DOP; the other five forms of inorganic nitrogen (NO3, NH4), phosphorus (PO4), silicon (SiO4), and carbon (DIC) nutrients; dissolved oxygen as an index of net photosynthesis; ammonifying and nitrifying bacteria; six groups of phytoplankton (diatoms, dinoflagellates, coccolithophores, colonial prymnesiophytes, microflagellates, and diazotrophs), for which cell counts were made at the species level during 2002, 2003, and 2004 cruises of the Polar Star, Healy, Mirai, Louis St. Laurent, Alpha Helix, Professor Khromov, and Nathaniel Palmer. We have additionally employed satellite algorithms to distinguish among the two groups of backscattering coccolithophores and diazotrophs, compared to the other phytoplankton groups. Finally, food web closures is effected in the model by consideration of fecal pellets of protozoan and copepod herbivores; as well as interactions of the benthic amphipod herbivores with sediment detritus.

In working towards our objective of running the ecological model over decadal time scales, we began with just the bulk chlorophyll of the total phytoplankton community over two- year (July 2002-September 2004), three-dimensional simulations of the Chukchi-Beaufort Sea region, using the data sets from the above cruises for validation. Least square fits of model output at various grid points, coincident with shipboard bottle data of silicate, nitrate, ammonium, phosphate, oxygen, and chlorophyll concentrations, have been performed. From our latest run, over the suite of observations for 2003 (1000-4000 data points), the correlation coefficients of model output and observations for silicate, nitrate and oxygen were highest (0.5-0.8) and lowest for ammonium and chlorophyll (<0.25). For the second simulated year of 2004 (500-2000 data points), the correlations were about the same, slightly higher for phosphate(0.58 versus 0.47), but lower for oxygen(0.42 versus 0.78).

We found that better agreement between simulated and observed chlorophyll stocks was obtained, if only upper mixed layer data points were included. The large simulated concentrations of algal biomass, which accumulated in the bottom of the model's water column after the spring bloom, may have been missed by ship bottle casts, due to the thinness of these layers. Better overall agreement between data and model output was also obtained if model results were lagged by a few weeks, indicating the importance of the simulation of the springtime retreat of the ice pack, and perhaps species succession of phytoplankton groups, not resolved by the present model formulation. Thus, future model runs will test model refinements: of the bacterial loop within the water column; benthos for better comparison with measured ammonium stocks; and addition of more functional groups of phytoplankton (Walsh and Dieterle, 2009).

IMPACT AND APPLICATIONS

National Security

The focus of this project on seasonally ice-free Alaskan coasts and shelves is in direct support of the ONR focus on ‘Coastal Effects of a Diminished-ice Arctic Ocean’ and littoral studies of interest to the

U.S. Navy. Given the continued warming and summer sea ice cover decrease in the Arctic during the past decades, this research will have broader and long-term impacts by facilitating studies of the potential increased activities along the seasonally ice-free northern Alaskan coasts and shelves. Such activities will change the strategic importance of the entire pan-Arctic region. The research will allow a better understanding and planning of current and future operational needs in support of the continued US tactical interests in the region.

Economic Development

Understanding and prediction of environmental conditions under a diminished-ice Arctic Ocean will have broader and long-term impacts by facilitating studies of the potential increased exploration of natural resources along the seasonally ice-free northern Alaskan coasts and shelves and of the use of northern sea routes from the Pacific Ocean to Europe. The research will allow a better understanding and planning of current and future operational needs in support of the expanding US commercial interests in the region.

Science Education and Communication

The project involves undergraduate, graduate, and postdoctoral education in research. The postdoctoral and graduate students will receive practical training in environmental modeling and/or analysis of model output and observational data. All PIs will present results of this research in undergraduate and graduate classes, at scientific meetings and in peer-reviewed literature.

RELATED PROJECTS

This grant is funded by the Office of Naval Research's National Oceanographic Partnership Program (NOPP), and builds on work done under the two following programs funded by NSF:

1. Study of Northern Alaska Coastal System (SNACS): Maslowski and Cassano (co-PIs)
2. Western Arctic Shelf Basin Interaction (SBI): Maslowski and Walsh (co-PIs)

More information about the two projects is available at www.oc.nps.navy.mil/NAME/name.html

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